

# The Earthquake Potential of the New Madrid Seismic Zone

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**Abstract** The fault system responsible for New Madrid seismicity has generated temporally clustered very large earthquakes in A.D. 900  $\pm$  100 years and A.D. 1450  $\pm$  150 years as well as in 1811–1812. Given the uncertainties in dating liquefaction features, the time between the past three New Madrid events may be as short as 200 years and as long as 800 years, with an average of 500 years. This advance in understanding the Late Holocene history of the New Madrid seismic zone and thus, the contemporary tectonic behavior of the associated fault system was made through studies of hundreds of earthquake-induced liquefaction features at more than 250 sites across the New Madrid region. We have found evidence that prehistoric sand blows, like those that formed during the 1811–1812 earthquakes, are probably compound structures resulting from multiple earthquakes closely clustered in time or earthquake sequences. From the spatial distribution and size of sand blows and their sedimentary units, we infer the source zones and estimate the magnitudes of earthquakes within each sequence and thereby characterize the detailed behavior of the fault system. It appears that fault rupture was complex and that the central branch of the seismic zone produced very large earthquakes during the A.D. 900 and A.D. 1450 events as well as in 1811–1812. On the basis of a minimum recurrence rate of 200 years, we are now entering the period during which the next 1811–1812-type event could occur.

## Introduction

Three major earthquakes having estimated moment magnitudes of  $M$  7–8, as well as several large aftershocks, struck the central United States in the winter of 1811–1812 (Atkinson and Hanks, 1995; Johnston, 1996; Hough *et al.*, 2000). On the basis of felt reports, these earthquakes are inferred to be among the largest known intraplate earthquakes in the world and to have been centered in the New Madrid seismic zone (NMSZ) (Johnston and Kanter, 1990). As demonstrated by the 2001,  $M$  7.7, Bhuj earthquake in Gujarat, India, very large earthquakes do occur in intraplate regions and can cause widespread liquefaction with little expression of faulting at the ground surface (Bendick *et al.*, 2001; Tuttle *et al.*, in press).

The 1811–1812 earthquakes destroyed several settlements along the Mississippi River and induced severe liquefaction and ground failure throughout the New Madrid region. A large liquefaction field ( $\sim 10,000$  km<sup>2</sup>) has been attributed to the 1811–1812 earthquakes (Fuller, 1912; Saucier, 1977; Obermeier, 1989). We now know that this liquefaction field is composed of prehistoric as well as historic sand blows (Tuttle and Schweig, 1995; Tuttle, 1999; Fig. 1). In addition, the 1811–1812 earthquakes caused minor structural damage as far away as Cincinnati, Ohio, and St. Louis, Missouri, and liquefaction more than 240 km from their in-

ferred epicenters (Street and Nuttli, 1984; Johnston and Schweig, 1996). An empirical relation between earthquake moment magnitude and distance to farthest liquefaction (Ambraseys, 1988) estimates that these earthquakes had magnitudes of  $M \geq 7.6$  (Tuttle, 2001a). Scenarios of fault rupture have been proposed that account for historical descriptions of the earthquakes and their effects, liquefaction features and related ground failures, structure of the seismogenic fault system, and present-day seismicity (Johnston and Schweig, 1996).

Johnston and Nava (1985) suggested a recurrence interval of 550 to 1200 years for  $M \sim 8$  earthquakes based on analysis of instrumental and historical seismicity in the New Madrid region. The geological record of earthquakes for the past 1200 years suggests a similar, albeit slightly shorter, recurrence interval for New Madrid events (Russ, 1982; Saucier, 1991; Vaughn, 1994; Craven, 1995; Kelson *et al.*, 1996; Tuttle *et al.*, 1996; Li *et al.*, 1998; Tuttle, 1999; Tuttle *et al.*, 1999; Broughton *et al.*, 2001; Cramer, 2001). A recent study of geodetic measurements made over a 7-year period concludes that either the recurrence interval exceeds 5000 years or that the magnitudes of 1811–1812 earthquakes are toward the lower end of the  $M$  7–8 range (Newman *et al.*, 1999). However, the geodetic analysis assumed an infinitely

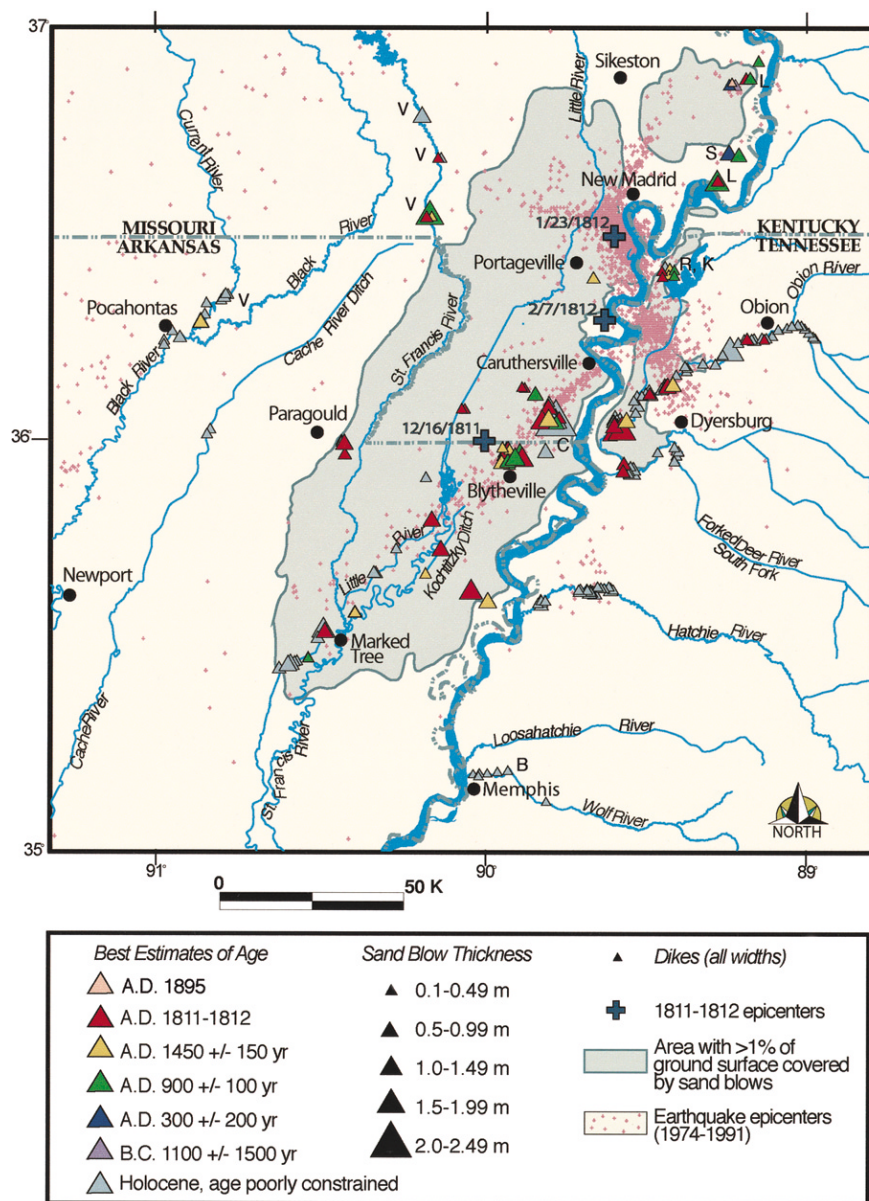


Figure 1. Map of NMSZ showing estimated ages and measured sizes of liquefaction features. Sand-blow thickness was measured adjacent to major vents and feeder dikes and represents minimum values of total thickness, since sand-blow surface morphology may have been altered slightly by erosion and more significantly by modern farming practices. All sites were discovered by us except R (Russ, 1982); S (Saucier, 1991); C (Craven, 1995); L (Li *et al.*, 1998); K (Kelson *et al.*, 1996); V (Vaughn, 1994); and B (Broughton *et al.*, 2001). Area of surficial sand-blow deposits is from Saucier (1977) and Obermeier (1989).

long, interplate fault zone and did not consider known physical characteristics of the NMSZ. Given that strain rates may vary temporally during and between earthquake cycles and that surface-strain rates may not reflect deeper crustal rates, a longer-term view of fault behavior that spans several earthquake cycles provides a more accurate characterization of earthquake recurrence. This article presents our findings that the NMSZ has produced earthquake sequences, like the 1811–1812 event and referred to here as New Madrid events,

on average every 500 years for the past 1200 years and therefore presents a significant hazard to the central United States.

### Timing of Prehistoric Earthquakes

Studies of liquefaction features at more than 250 sites across the New Madrid region provide new insights about past strong earthquakes. At all of these sites, we measured and described liquefaction features and collected available

material for dating. At 26 of the sites, many of them archeological sites, we conducted detailed subsurface investigations of sand blows, or sand deposits vented to the ground surface as the result of liquefaction, and the related stratigraphy (Fig. 1). In addition, we reviewed the results of investigations at 12 other liquefaction sites (Russ, 1982; Saucier, 1991; Vaughn, 1994; Craven, 1995; Wesnousky and Johnson, 1996; Li *et al.*, 1998) and included them in our analysis of prehistoric earthquakes.

Our detailed studies of liquefaction sites involved the logging or mapping at scales of 1:10 or 1:20 of trench walls and cut-bank exposures of rivers and drainage ditches. Logs, descriptions of liquefaction features and of structural and stratigraphic relations, results of radiocarbon dating and artifact analysis, and interpretations are presented elsewhere (Tuttle, 1999, 2001b; Tuttle *et al.*, 1998, 1999, 2000) and are not repeated here. Those interested in a detailed explanation of methodologies used in our paleoliquefaction studies in the New Madrid region are referred to Tuttle (1999, 2001a). During these studies, we have estimated the ages of liquefaction features and gathered information about the size, stratigraphy, and spatial distribution of both historic and prehistoric liquefaction features. Characterization of sand blows that formed during the 1811–1812 New Madrid earthquakes has been crucial for the interpretation of prehistoric liquefaction features and paleoevents in the region.

Age estimates of liquefaction features are based on radiocarbon dating of charcoal and plant remains and archeological analysis of Native American artifacts in soil horizons buried by and developed in or above sand blows (Fig. 2). Charcoal and plant remains found at archeological sites are usually from Native American occupation horizons and features and therefore are probably derived from trees or other plants growing near the site before burning or burial. Materials collected above sand blows provide minimum dates, whereas materials below sand blows provide maximum dates. Some materials within sand blows provide contemporary dates. Age estimates of liquefaction features are derived from two-sigma calibrated radiocarbon dates. Timing of events is interpreted from age estimates of liquefaction features at many sites across the region, with more weight given to features with well-constrained ages. Large sand blows that formed since A.D. 1650 are usually attributed to the 1811–1812 earthquakes. An exception is a cluster of small sand dikes at the Burkett archeological site, about 33 km east of Sikeston, that may have formed during the 1895, M 6.6, Charleston, Missouri, earthquake (Tuttle, 2001b).

In cases where the ages of liquefaction features are not well constrained by radiocarbon dating, artifact stratigraphy and soil development are sometimes used to narrow the age estimate. This practice has been particularly helpful for estimating the age of liquefaction features that formed during the past 600 years. Because  $^{14}\text{C}$  in the atmosphere has fluctuated so much owing to burning of fossil fuels and testing of nuclear devices, calibrated radiocarbon dates for this time period typically range from A.D. 1400 to 1955. At several

sites, we have found Native American-occupied soil horizons and features such as pits and wall trenches that contain diagnostic artifacts of the Late Mississippian cultural period (circa A.D. 1400–1650) and that overlie or intrude, and therefore postdate, sand blow deposits. Even though radiocarbon dating of material collected above the sand blows may provide maximum age estimates of A.D. 1950, the artifact stratigraphy indicates that these sand blows formed before A.D. 1650. In cases where they directly overlie soil horizons containing Late Mississippian artifacts, sand blows are thought to have formed during that cultural period. However, in cases where they overlie soil horizons in which Late Mississippian artifacts occur 10–20 cm below the contact, sand blows are interpreted as being historical in age.

Following lines of reasoning briefly described previously, age estimates of liquefaction features throughout the region cluster around A.D.  $1810 \pm 130$  years (the 1811–1812 earthquakes), A.D.  $1450 \pm 150$  years, and A.D.  $900 \pm 100$  years, interpreted as the dates of causative earthquakes. The dates represent the mean and the range during which we are confident that the earthquakes are likely to have occurred. Liquefaction evidence also exists for at least two large earthquakes before A.D. 800, but their ages remain poorly constrained.

### Source Area and Magnitudes of Prehistoric Earthquakes

A strong, spatial correlation between historical and prehistoric sand blows and the contemporary NMSZ provides good evidence that the NMSZ was the source for two prehistoric events, as well as the 1811–1812 earthquake sequence. With the exception of a sand blow on the Current River, which might have formed as a result of a local earthquake centered near Pochontas, Arkansas (Tuttle *et al.*, 1998), the spatial distribution of sand blows thought to have formed about A.D. 1450 is only slightly less extensive than the distribution of 1811–1812 sand blows (Fig. 3). To date, sand blows that formed during the A.D. 1450 event have not been identified south of Marked Tree, Arkansas, east of Dyersburg, Tennessee, or north of New Madrid, Missouri. The spatial distribution of sand blows that formed about A.D. 900 is also similar to that for 1811–1812 sand blows (Fig. 3). Apparent differences in these distributions occur in the vicinity of Dyersburg and Paragould, Arkansas, where, to date, no paleoliquefaction feature has been attributed to the A.D. 900 event. Liquefaction features north of New Madrid have been attributed to the A.D. 900 and 1811–1812 events. Although the full extent of liquefaction has not yet been defined for either the A.D. 1450 or the A.D. 900 prehistoric event, similarities in the distributions of historical and prehistoric sand blows are striking.

Many historical sand blows in the New Madrid region are composed of several, fining-upward depositional units, with silt layers separating fining-upward sandy units with little to no intervening soil development, and have been at-



Figure 2. Earthquake chronology for NMSZ from dating and correlation of liquefaction features at sites (listed at top) along NE–SW transect across region. Conservatively, we use only two-sigma calibrated radiocarbon dates and show the maximum possible age range based on minimum and maximum age constraints for individual liquefaction features. Native American occupation horizons and features and soil development are also considered when estimating ages of features. Some sites show age estimates for more than one feature related to different events (e.g., Eaker 2 and L2). Inferred timing of events is shown with colored bands. Sites Current River 1 and 8 are not along NE–SW transect but are located near Pocahontas, Arkansas, in the western lowlands (see Fig. 1).

induced by another strong earthquake. Owing in part to their compound nature, sand blows in the New Madrid region are large compared with sand blows worldwide. However, even individual depositional units constituting the sand blows are large, suggesting very large earthquakes. For comparison, sand blows that formed during the 1895 **M** 6.6 Charleston, Missouri, earthquake are considerably smaller, ranging in size from 0.15 to 3 m long in plan view (Metzger *et al.*, 1998). Also, liquefaction-related ground failures resulting from the 1895 earthquake apparently are limited to a 15-km<sup>2</sup> area near the inferred epicenter (Powell, 1975; Obermeier, 1989).

Like those that formed in 1811–1812, many sand blows attributed to the A.D. 1450 and A.D. 900 New Madrid earthquakes are compound structures composed of one to four



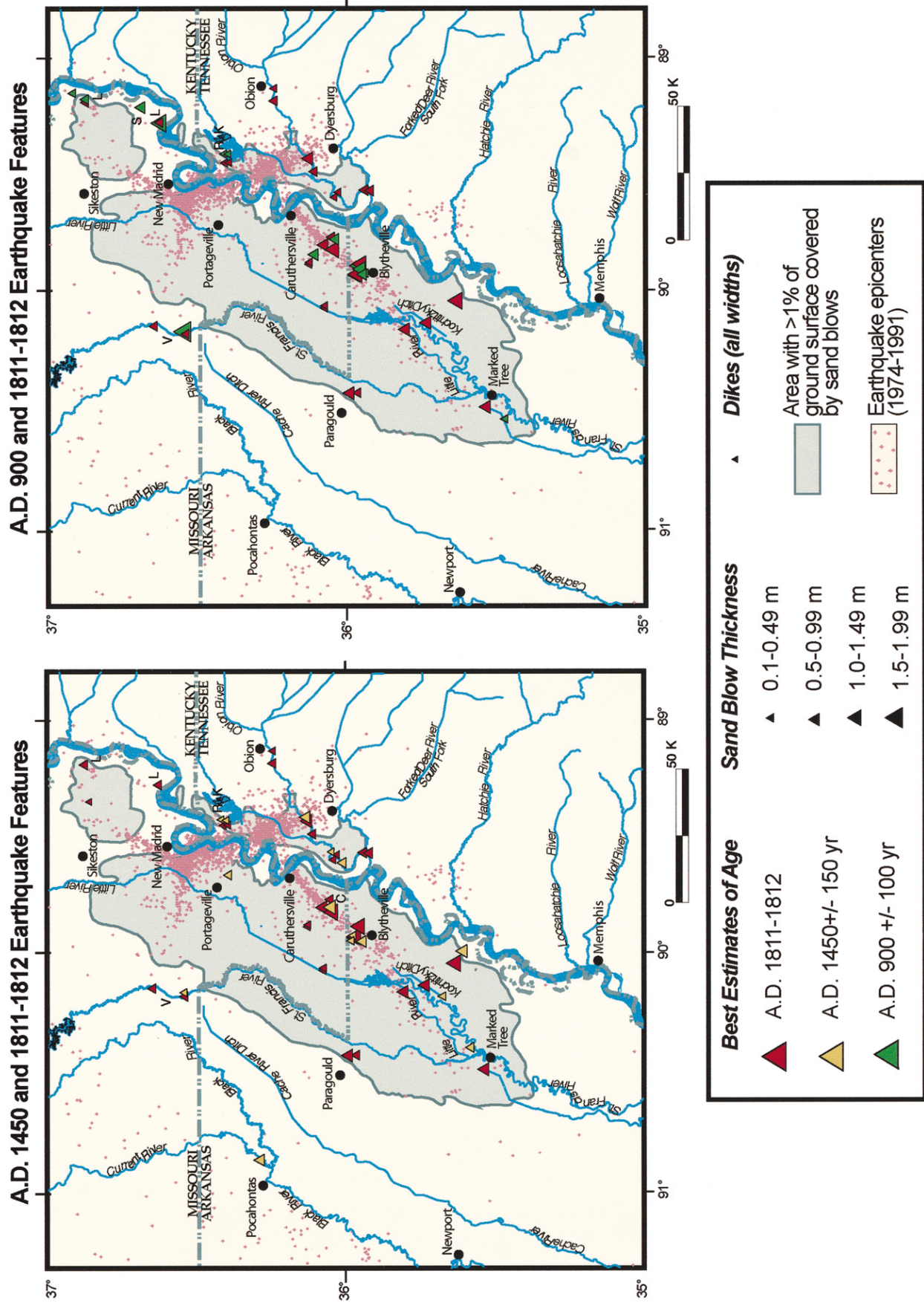


Figure 3. Maps showing spatial distributions and size of sand blows and other earthquake-related features attributed to A.D. 1450 and A.D. 900 events. Locations and sizes of sand blows related to 1811–1812 earthquake sequence shown for comparison.

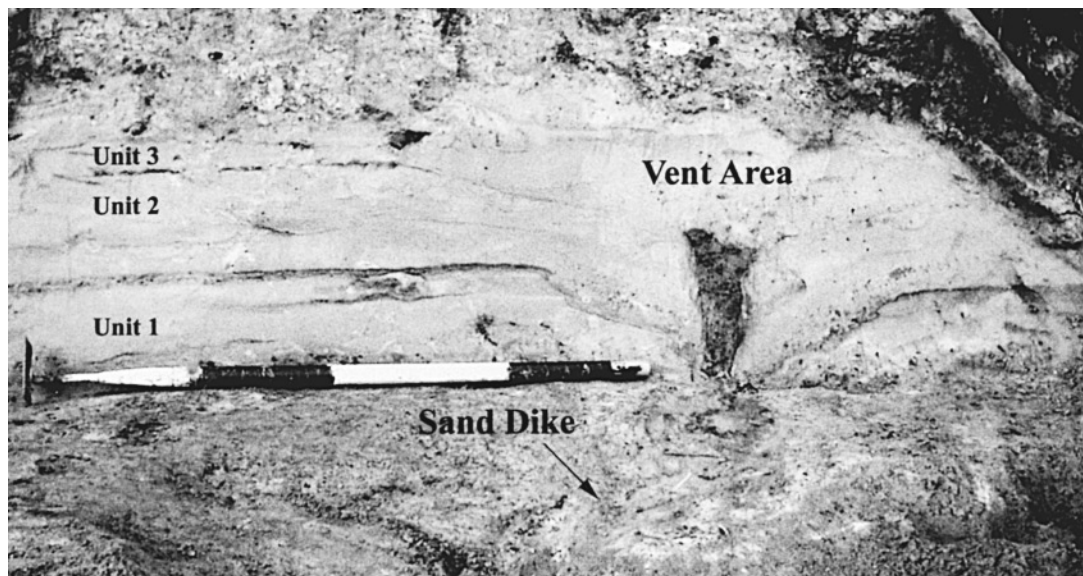


Figure 4. Sand blow along Obion River near Dyersburg, Tennessee, composed of three distinct depositional units separated by thin silt layers. Radiocarbon dating indicates that this sand blow formed during 1811–1812 earthquakes. Units 1, 2, and 3 are about 17 cm, 19 cm, and 12 cm thick, respectively. The hoe is about 1 m long. Photograph by M. Tuttle.

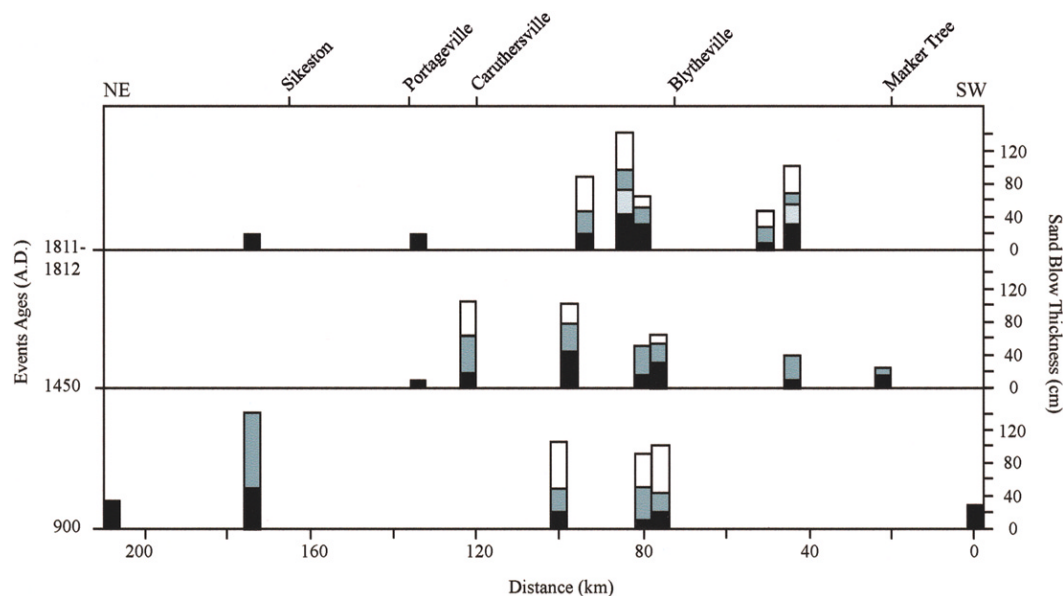


Figure 5. Total thickness of sand blows as well as thickness of their major depositional units, denoted by shading, are similar for historical and prehistoric sand blows. Data are for sites where sand blows were logged in detail. Depositional units composing sand blows probably reflect individual large earthquakes within a sequence.

fining-upward units that are 0.2–1.4 m thick (Figs. 1 and 5). Individual depositional units of the prehistoric sand blows are similar in thickness and lateral extent to the 1811–1812 sand blows. The thickness of prehistoric sand blows and their internal stratigraphy suggest that the A.D. 1450 and A.D. 900 events were associated with similar levels of ground shaking and therefore were similar in magnitude to the 1811–1812

earthquakes. In addition, the compound nature of the prehistoric sand blows suggests that prehistoric events included several very large earthquakes closely clustered in time. The large size of sand blows and their compound nature argue for liquefaction produced by a few very large earthquakes over a period of months, rather than more numerous, smaller earthquakes over a period of hundreds of years.



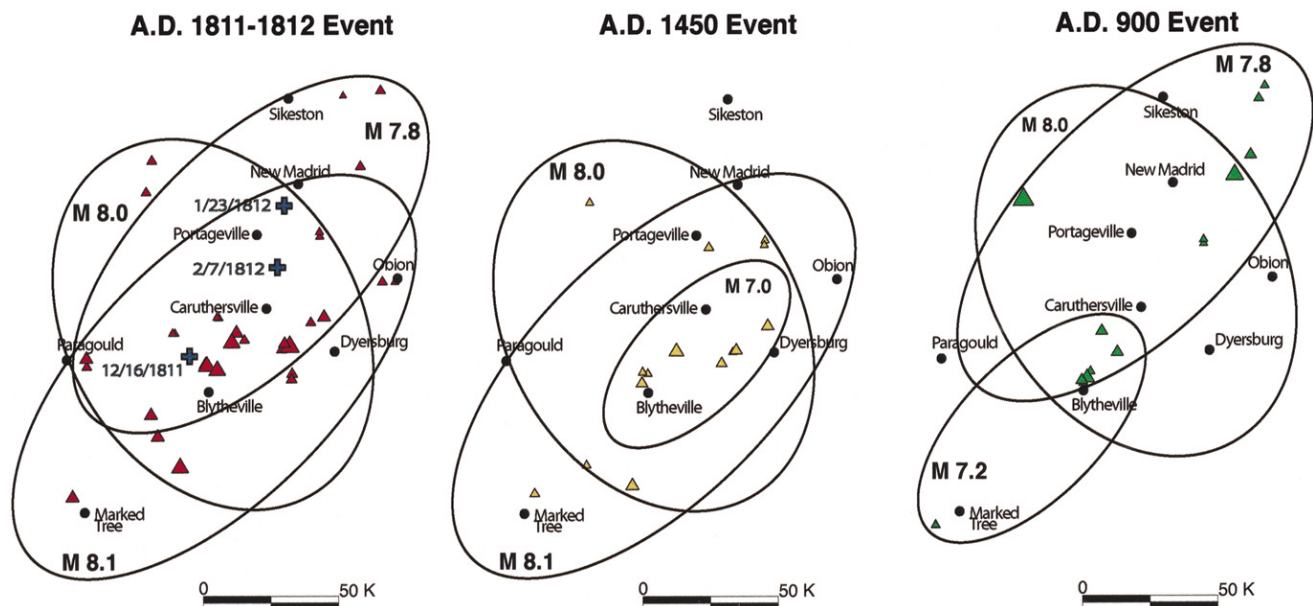


Figure 6. Liquefaction fields for 1811–1812, A.D. 1450, and A.D. 900 events as interpreted from spatial distribution and stratigraphy of sand blows (see text and Tuttle, 1999). Liquefaction fields for 1811–1812 earthquakes are proportional in size to the estimated magnitudes derived by Johnston (1996). Magnitudes of individual earthquakes in A.D. 1450 and A.D. 900 are inferred on basis of liquefaction fields compared with those related to 1811–1812 earthquakes.

The spatial distribution of sand blows that formed in 1811–1812 can be explained with three liquefaction fields, taking into account the number and thickness of the major depositional units constituting individual sand blows (Figs. 5 and 6). The 1811–1812 sand blows typically have a maximum of three major depositional units. Several sand blows in the vicinity of Blytheville are characterized by a fourth sedimentary unit that may have formed as a result of a large aftershock, possibly the  $\sim M 7.2$  earthquake on 16 December. However, there are not enough data regarding this fourth unit to define a separate liquefaction field at this time. The liquefaction fields for the 1811–1812 earthquakes are constrained by field data on sand blows, they encompass the preferred fault-rupture scenario for the 1811–1812 event proposed by Johnston and Schweig (1996), and they are proportional in size to the estimated magnitudes derived by Johnston (1996) for the three largest earthquakes. Prehistoric liquefaction features can be modeled in a similar manner as the 1811–1812 earthquake sequence. The spatial distribution and internal stratigraphy of sand blows attributed to the A.D. 900 event are similar to sand blows that formed in 1811–1812. Therefore, the liquefaction fields encompassing sand blows attributed to the A.D. 900 event are similar to the 1811–1812 liquefaction fields, except in the southern part of the seismic zone, where one field is smaller because sand blows of this age have not been found near Dyersburg or Paragould. A.D. 900 sand blows near Blytheville and Caruthersville are composed of three depositional units and therefore are attributed to three different events whose li-

quefaction fields overlap (Figs. 5 and 6). The distribution and internal stratigraphy of sand blows attributed to the A.D. 1450 event also can be fit with three liquefaction fields. Other interpretations of sand-blow distribution and stratigraphy are possible, but those presented here seem the most reasonable based on currently available data.

Our preferred interpretation of prehistoric sand blows suggests that at least two earthquakes occurred in A.D. 1450 and A.D. 900 that were similar in size and location to the largest 1811–1812 earthquakes. In addition, we suggest that (1) faults, possibly the Reelfoot fault, associated with the northwest-oriented, central branch of the NMSZ, are the source of similar-size earthquakes during all three sequences; (2) faults associated with the southern branch of the seismic zone may have ruptured during each sequence but produced a slightly smaller-magnitude earthquake in A.D. 900; and (3) faults associated with the northern branch of the NMSZ may have ruptured in A.D. 900 and 1812, but not in A.D. 1450.

#### Recurrence Interval of New Madrid Events and Fault Behavior

Estimated uncertainties on the timing of the prehistoric events ( $A.D. 900 \pm 100$  years and  $A.D. 1450 \pm 150$  years) allow the intervals between the last three New Madrid events to be as short as 200 years or as long as 800 years (Fig. 7). Some of the variability in these intervals is due to uncertainties in the radiocarbon dating itself and in dating hori-

zons that predate and postdate sand blows. Recently, Cramer (2001) performed a recurrence-interval analysis for New Madrid earthquakes by using our estimated dates and their uncertainties and Monte Carlo sampling of 1000 recurrence intervals. The results can be fit by a lognormal distribution (Savage, 1991) with a median value of 440 years and a mean value of 498 years. At the 95% confidence level, the estimated recurrence interval for  $M > 7$  New Madrid earthquakes ranges from 162 to 1196 years.

There is no reason to assume a constant earthquake-recurrence rate anywhere and certainly not in intraplate regions like the NMSZ, where the tectonic driving forces are not understood. If the rate of strain accumulation in the NMSZ is relatively constant, however, the cumulative moment released during an earthquake sequence may affect the time until the next event. Additional study may better constrain ages of older liquefaction features in the region and extend the history of earthquakes to at least 6000 B.P. and possibly 12,000 B.P. Developing a longer paleoseismic history could potentially define additional earthquake cycles and help determine whether the rate of very large earthquakes during the past 1200 years reflects the Holocene rate. In addition, a longer paleoseismic history may reveal when the current period of seismic activity began, help to determine what process "turned on" the NMSZ, and thereby improve our understanding of seismogenesis in intraplate settings.

Earthquakes in the NMSZ are produced by a network of intersecting faults, so fault interactions are likely to be complex, with strain release on one fault increasing strain on others (Schweig and Ellis, 1994). Our liquefaction data suggest that faults associated with the central branch of the NMSZ ruptured to produce  $M \geq 7.6$  earthquakes during the A.D. 900, A.D. 1450, and 1811–1812 events (Fig. 6). This repeated pattern of behavior for the central branch of the seismic zone may have implications for future New Madrid

events. In contrast, it appears that different portions of the southern branch of the NMSZ may have ruptured during the 1811–1812, A.D. 1450, and A.D. 900 New Madrid sequences (Fig. 6).

## Conclusions

Through the study of earthquake-induced liquefaction features, considerable progress has been made toward developing an earthquake chronology and assessing the behavior and earthquake potential of the NMSZ. Age estimates of liquefaction features across the region cluster around A.D.  $1810 \pm 130$  years, A.D.  $1450 \pm 150$  years, and A.D.  $900 \pm 100$  years, interpreted as the dates of causative earthquakes. We have liquefaction evidence for two events before A.D. 800, but their ages are not yet well constrained.

Prehistoric sand blows, like those that formed during the 1811–1812 event, are probably compound structures resulting from multiple earthquakes clustered in time, suggesting that the A.D. 900 and A.D. 1450 events were also earthquake sequences. In addition, the size, internal stratigraphy, and spatial distributions of prehistoric sand blows indicate that the A.D. 900 and A.D. 1450 earthquakes had similar source zones and magnitudes to the three largest shocks in the 1811–1812 sequence. More specifically, characteristics of the sand blows suggest that faults associated with the central branch of the seismic zone were responsible for  $M \geq 7.6$  earthquakes during the A.D. 900, A.D. 1450, and 1811–1812 events. Liquefaction data indicate that New Madrid events occurred every  $500 \pm 300$  years during the past 1200 years. Furthermore, this recurrence rate for very large earthquakes is not easily reconciled with the small amount of crustal deformation observed in the region, suggesting that the NMSZ became active during the Quaternary and that New Madrid earthquakes may be temporally clustered in this intraplate region.

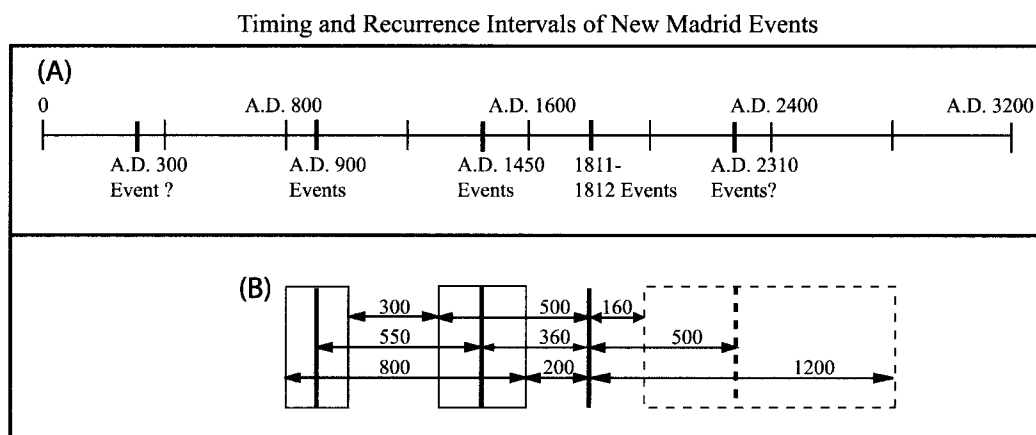


Figure 7. (A) Time line illustrating A.D. 900, A.D. 1450, and 1811–1812 events and projection to next New Madrid event circa A.D. 2310, based on average recurrence interval of 500 years. (B) Uncertainties in timing of New Madrid events yield estimated recurrence intervals that vary from about 160 to 1200 years (Cramer, 2001).



Admittedly, 1200 years is a short time span in the history of the NMSZ on which to characterize its long-term behavior, and the seismic zone could behave differently in the future than it has in the past. However, on the basis of paleoseismic data acquired so far, we propose that sequences of very large earthquakes will continue to occur at a rate similar to that of the recent past, or on average every 500 years.

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